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# INTEGRITY OF NEIGHBOURING COOLANT CHANNELS IN THE EVENT OF A SINGLE COOLANT CHANNEL FAILURE IN A PHWR

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## ABSTRACT

The present paper develops a methodology to carry out integrity assessment of core components in the event of combined pressure tube and calandria tube failure in a pressurised heavy water reactor (PHWR). This accident which is considered as the design basis under single failure category results into impact loading on neighbouring channels, core components and main reactor vessel called calandria. A three dimensional coupled fluid-structure interaction code FLUSHEL is tailord to determine the response of neighbouring channels for this condition. A number of failure modes are assumed and adequacy of channel design is demonstrated for such extreme loading conditions.

## INTRODUCTION

The calandria of Indian 500 MWe PHWR houses horizontal coolant channels which are individually surrounded by calandria tubes to separate them from the outside moderator which is a low pressure system. The coolant channels accomodate fuel bundles which are cooled by heavy water coolant. Fast fracture of zircaloy-2 / zircaloy-2.5% niobium pressure tubes has been a major concern in the PHWR core component design. In view of the reported failures of pressure tubes due to combination of high residual stresses resulting from over extended rolled joints, enhanced hydrogen pick up rate due to contact between sagging pressure tube on the calandria tube in a channel [1,2], Indian PHWRs have adopted zero clearance improved rolled joints and four spacers in each channel [fig.1]. However, on account of critical design of these tubes one of the important single failure event under loss of coolant accident is postulated as combined failure of pressure tube and calandria tube.

The failure of pressure tube inside the calandria has a number of sequential events which may be described as crack tip propagation, decompression of high enthalpy coolant through crack opening, shock wave propagation, phase change of fluid and associated bubble dynamics along with fluid-structure interaction. It is noted that the transient phenomenon is a complex one and as such all the cases described above cannot be tackled in a single study. The reported studies [3-5] for other PHWRS have not considered the effect of channel arrays along with fluid elastic coupling & multiple wave reflection effects in the early stage of discharge including initial shock wave. These considerations result into a complex pressure field in the vicinity of an accident and resultant loading on neighbouring channels has to be accounted in a 3-D formulation as membrane stresses are important to determine the local collapse. Moreover the channels are supported at the ends. Hence they are subjected to vibratory motion and the bending stresses due to the impulsive loading are also significant depending on the location and size of rupture.

The present paper develops a methodology to analyse this problem with due consideration to above mentioned effects to obtain the impulsive loading on neighbouring channels near an accident site in a coupled manner. The problem has been analysed with the computer code FLUSHEL which is a general purpose, 3-D finite element code for fluid-shell interaction problems. The structure is modelled with nine noded quadratic lagrangian degenerate shell elements and the fluid is modelled with eight noded trilinear brick elements with acoustic assumptions.The two domains are analysed in a coupled manner using staggered solution scheme of time integration with explicit-implicit partitioning of fluid and shell meshes. The theoretical details of these codes are available in [6-8].

## NUMERICAL MODEL

Fig 2 shows the finite element models of 2 X 3 reactor channels and surrounding moderator built up to obtain the response of neighbouring channels C2-C6 near an accident site at channel C1 for a typical 500 MWe PHWR. The channels simulate the stiffness of pressure tube and massess of both calandria tube and pressure tube along with the fuel bundles and coolant are lumped on individual channels. This assumption is justified as the orders of pressure due to accident are sufficient to cause collapse of calandria tubes on its corresponding pressure tubes. The size of the model is such that the total wave reflection effects are simulated on target channels C2/C4 and results do show lower responses in channels C3 and C6 which are away from the accident site. One end of the channels is assumed to be fixed with the tube sheet and symmetry condition is applied on the other end. In the fluid mesh of moderator Sommerfeld radiation boundary condition is applied at the edges to avoid any spurious wave reflection from mesh boundary. However, on the left edges of channel C1 and C4 and right edges of channel C3 and C6 a rigid boundary is assumed which enables simulation of wave reflection effects from other channels which are not modelled. Channel normal accelerations are transferred to the fluid boundary and fluid pressure is applied to the channel surfaces at each time step in an iterative manner till the convergence is achieved.

The other important parameter in this transient study is the size and location of failure of channel C1. In this paper following cases are studied. (i) Axial hair line crack of 1080 mm / 2160 mm at mid span of C1 channel causing line wave loading. (ii) Complete circumferential break of channel C1 at mid span causing line wave loading (hair line crack size 335.4 mm) (iii) Predominantly axial slit of size 162.1 mm with a circumferential width of 113.1 mm (assuming an opening of 1/3 of circumference) at the mid span of channel C1 causing surface wave loading. This is referred as fish mouth opening. (iv) Complete circumferential double ended rupture of size 339.4 mm circumferentially causing surface wave loading. This assumes complete vanishing of channel C1 at mid span with an axial length of 54 mm.

The basis for selecting crack openings is based on the criteria of fully open slit where crack length should be at least six times the radius of the tube [4] which is equivalent to double ended rupture. In the last two cases of surface wave loading the slit area has been taken equal to twice the cross-sectional area of the failed tube. The shock pressure at the source is followed by quasi static pressure after flashing, these are calculated from the following formulae based on compressible fluid assumptions and experimental results [4-5].

$$( p + B )\rho^{-n} = \text{constant} \qquad (1)$$

$$T_{qs} = T_{pc} - 1.26 \frac{\rho_g \, h_{fg}}{\rho_f \, c_{pf}} \qquad (2)$$

This gives a shock pressure (p shock) of 6.186 MPa and quasi-static pressure after flashing (pqs) of 5.426 MPa, the corresponding saturation pressure at Tqs. Here B=296 MPa and n=7.4 are constants for equation of state, h, cp & $\rho$ represent enthalpy,specific heat and density respectively for heavy water coolant at temperature Tpc with suffixes f and g for fluid and vapour phases respectively. In the present case the duration of initial shock is decided by time of crack propagation and relaxation time for nonequilibrium thermodynamic condition. Once saturation pressure is reached the other transients due to bubble growth takes over the initial shock phenomenon. Here it may be noted that in different cases mentioned above a multiple number of sources are active simultaneously and spherical symmetry assumption of a single source is not valid for local loading of neighbouring channels.

## INTEGRITY ASSESSMENT OF CHANNELS

Fig 3 shows pressure history around the target channel C2 at $\theta$ = 0 deg, 60 deg, 120 deg and 180 deg for axial break of 1080 mm with line wave loading originating at C1 at $\theta$ = 180 deg. Fig.4 and 5 show membrane and bending stress intensities for C2 and C3 channels at $\theta$ = 0 deg and $\theta$ = 90 deg for this load case. The peak pressure values along with resulting maximum membrane and bending stress intensities for channels C2 through C5 are summarized in table 1 for all the cases of line wave loading ( cases (i) and (ii) discussed above). Table 2 presents peak pressures and maximum membrane and bending stress intensities for surface wave loading (Cases (iii) and (iv) mentioned above).

It may be noted that for line wave loading,channels C3 and C6 see less pressure compared to target channels C2 and C4. The pressure loading for channel C5 is in between the above two cases. For axial break the target channels C2 and C4 are subjected to same orders of pressure loading. The pressure on C4 is slightly higher than C2 due to simulation of a rigid boundary left to channel C4 for considering wave reflection effects. Similar observation is noted for circumferential line break also. In the present study C4, C5 and C6 channels are subjected to unsymmetric loading while, C2 and C3 channels are subjected to symmetric loading. Combinations of the two cases could be used to obtain response due to randomly located break along the periphery of a typical channel.

In case of surface wave loading originating from failure of a portion of channel C1 again it is noticed that target channels C2 and C4 are subjected to higher pressure loading compared to channels C3 and C6 which are away from location of failure. Again the pressure loading for channel C5 lies in between the two cases and pressure loading on channel C4 is more than channel C2 due to reasons given above.

## CONCLUSIONS

The transient analyses carried out with code FLUSHEL for pressure tube failure accident demonstrate the capability to couple a fluid transient code with a structural dynamics code to obtain a coupled solution for local integrity assessment of PHWR core components. The 2 X 3 channel model with appropriate boundary conditions simulates all the aspects of wave loading, multiple reflections and free transmission between the ligaments of channels. The model gives simple but realistic result for shock loading of reactor channels which is consistent with the actual physical situation. The assumption of collapse of calandria tube is justified as theoretical collapse pressure of calandria tube is about 0.366 MPa which is very low compared to the order of pressure developed around the neighbouring channels. The pressure tubes near an accident site are not likely to collapse on account of internal pressure and its theoretical collapse pressure of 9.18 Mpa. The stress intensities obtained in this analysis can be suitably combined with other loadings to satisfy the design requirements at appropriate service level. Further studies have been initiated to analyse the other transient cases and suitable fluid models are being developed to include phase change and effect of bulk pressure/temperature rise on reactor channels which is important for the integrity of core components and calandria shell.

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Table 1 Line Wave Loading of Channels

| | Pressure ( M Pa) | | | Membrane Stress Intensity (M Pa ) | | | Bending Stress Intensity ( M Pa) | | |
|---|---|---|---|---|---|---|---|---|---|
| Channels | Axial Break 1 | Axial Break 2 | Circ. Break 3 | Axial Break 1 | Axial Break 2 | Circ. Break 3 | Axial Break 1 | Axial Break 2 | Circ. Break 3 |
| C 2 | 4.25 | 5.47 | 2.37 | 81.7 | 81.0 | 48.7 | 98.9 | 104.0 | 44.6 |
| C 3 | 3.58 | 5.05 | 1.80 | 45.7 | 60.1 | 19.6 | 69.3 | 91.6 | 32.2 |
| C 4 | 4.31 | 5.68 | 2.64 | 53.4 | 67.6 | 41.6 | 89.8 | 111 | 46.6 |
| C 5 | 4.07 | 5.42 | 2.25 | 49.7 | 64.2 | 34.6 | 50.8 | 63.5 | 24.1 |
| C 6 | 3.61 | 5.06 | 1.77 | - | - | - | - | - | - |

1 Axial break size 1080 mm. 2 Axial break size 2160 mm
3 Circumferential break size 339.4 mm

Table 2. Surface Wave Loading of Channels

| | Pressure (M Pa) | | Membrane Stress Intensity (M Pa) | | Bending Stress Intensity (M Pa) | |
|---|---|---|---|---|---|---|
| Channels | F. M. Opening 1 | D. E. Opening 2 | F. M. Opening 1 | D. E. Opening 2 | F. M. Opening 1 | D. M. Opening 2 |
| C 2 | 4.16 | 4.26 | 117 | 114 | 100 | 104.0 |
| C 3 | 3.29 | 3.34 | 44.7 | 48.8 | 65.9 | 69.9 |
| C 4 | 4.42 | 5.16 | 60 | 88.9 | 97.4 | 110.0 |
| C 5 | 3.97 | 4.10 | 70.5 | 76.7 | 51.6 | 59.2 |
| C 6 | 3.29 | 3.36 | - | - | - | - |

1 Fish mouth opening 162.1 x 113.1 sq mm
2 Double ended opening 54 x 339.4 sq mm

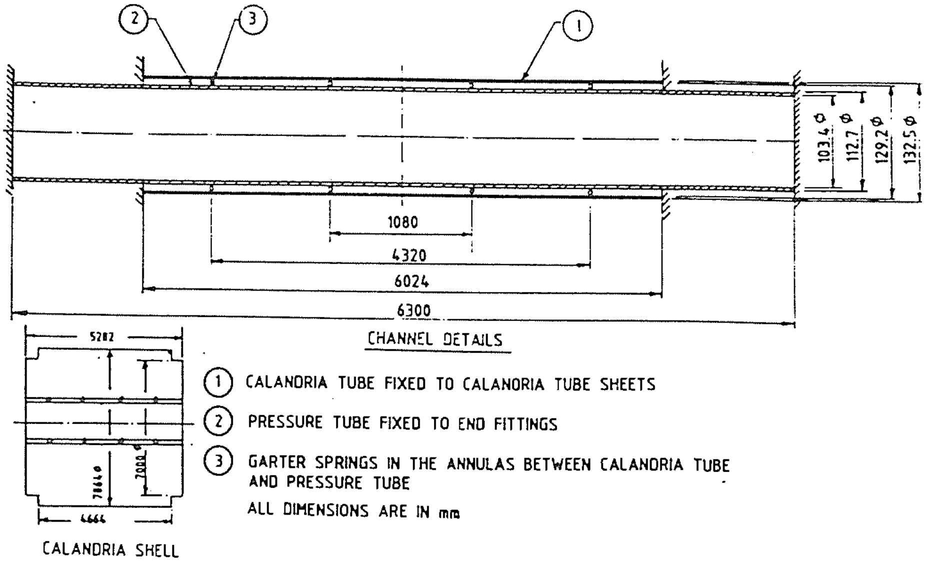

FIG.1 A TYPICAL ARRANGEMENT OF REACTOR CHANNEL IN 500 MWe PHWR

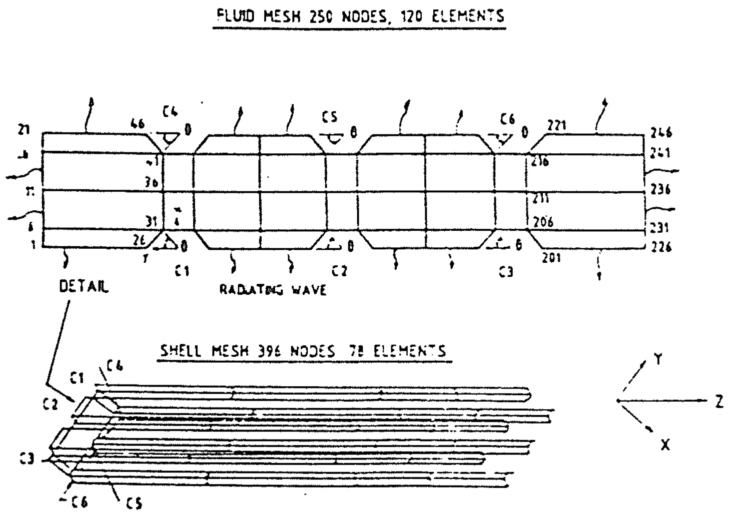

FIG. 2 THREE DIMENSIONAL FLUID / SHELL MODELS OF MODERATOR/CHANNELS IN 500 MWe PHWR

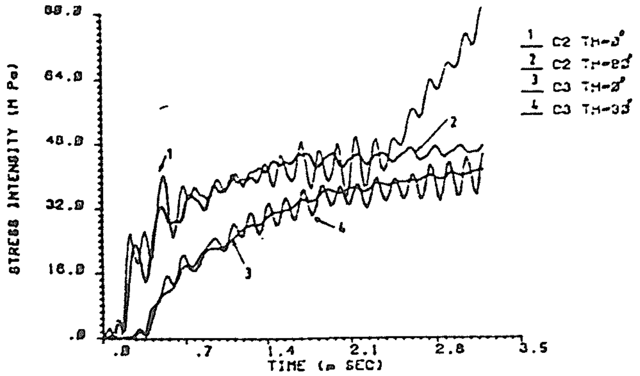

FIG 4 MEMBRANE STRESS AROUND C2/C3 CHANNELS (1 M AXIAL BREAK)

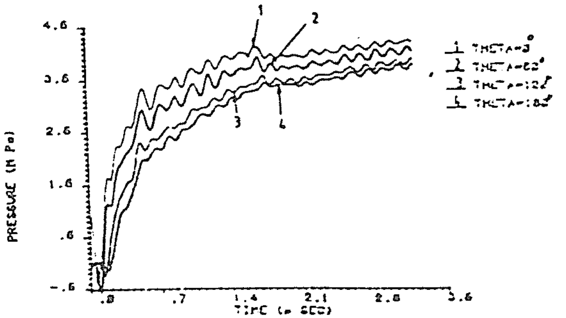

FIG 3 PRESSURE HISTORY AROUND C2 CHANNEL (1 M AXIAL BREAK)

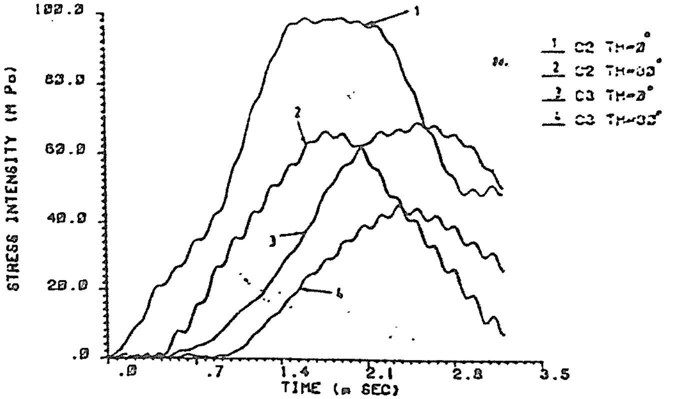

FIG. 5 BENDING STRESS AROUND C2/C3 CHANNELS (1 M AXIAL BREAK).